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June 3, 1996

Dr. Harold Hawkins & Dr. Robert Gisiner
Code 342PS
ONR
800 North Quincy Street
Arlington, VA 22217-5660

RE: N00014-94-1-0692 - Progress Report

Dear Drs. Hawkins & Gisiner:

On behalf of Peter L. Tyack, please find enclosed three copies of a reprint entitled "Onboard Acoustic Recording from Diving Elephant Seals" which Dr. Tyack is submitting to fulfill the progress report requirement for the time periods ending 12/95 and 6/96.

If there is anything further which you require, please let me know.

Sincerely,

Jane E. Marsh

Jane E. Marsh
Senior Staff Assistant
Biology Department
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enclosures

xc: DTIC, Ft. Belvoir, VA (2 copies)
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IN REPLY REFER TO:

4330
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From: Director, Office of Naval Research, Seattle Regional Office, 1107 NE 45th St., Suite 350, Seattle, WA 98105

To: Defense Technical Center, Attn: P. Mawby, 8725 John J. Kingman Rd., Suite 0944, Ft. Belvoir, VA 22060-6218

Subj: RETURNED GRANTEE/CONTRACTOR TECHNICAL REPORTS

1. This confirms our conversations of 27 Feb 97 and 11 Jul 97. Enclosed are a number of technical reports which were returned to our agency for lack of clear distribution availability statement. This confirms that all reports are unclassified and are "APPROVED FOR PUBLIC RELEASE" with no restrictions.

2. Please contact me if you require additional information. My e-mail is *silverr@onr.navy.mil* and my phone is (206) 625-3196.

ROBERT J. SILVERMAN

ONBOARD ACOUSTIC RECORDING FROM DIVING ELEPHANT SEALS

by

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Running title: Acoustic Recording from Elephant Seals

ABSTRACT

This study was the first phase in a long term investigation of the importance of low frequency sound in the aquatic life of northern elephant seals, *Mirounga angustirostris*. By attaching acoustic recording packages to the backs of six translocated juveniles, we aimed to determine the predominant frequencies and sound levels impinging on them, and whether they actively vocalize underwater, on their return to their rookery at Año Nuevo, California, from deep water in Monterey Bay. All packages contained a Sony digital audio tape recorder encased in an aluminum housing with an external hydrophone. Flow noise was minimized by potting the hydrophone in resin to the housing and orienting it posteriorly. The diving pattern of four seals was recorded with a separate time-depth recorder or a time-depth-velocity recorder. Good acoustic records were obtained from three seals. Flow noise was positively correlated with swim speed, but not so high as to mask most low frequency sounds in the environment. Dominant frequencies of noise impinging on the seals were in the range, 20-200 Hz. Transient signals recorded from the seals included snapping shrimp, cetacean vocalizations, boat noise, small explosive charges, and seal swim strokes, but no seal vocalizations were detected. During quiet intervals at the surface between dives, the acoustic record was dominated by respiration and signals that appeared to be heartbeats. This study demonstrates the feasibility of recording sounds from instruments attached to free-ranging seals, and in doing so, studying their behavioral and physiological response to fluctuations in ambient sounds.

INTRODUCTION

The sea is noisy. Wind, surf and wave action, current induced shifts in substrate, breaking ice, and seismic activity contribute to a fluctuating ambient noise level. Human-generated underwater noise originates from a variety of operations such as ship traffic (merchant ships, icebreakers, naval ships, fishing vessels, scientific ships and offshore supply ships) and offshore industrial activities (seismic exploration, construction work, drilling and oil and gas production, and scientific ocean sensing)(Richardson *et al.* 1995). Marine animals as diverse as snapping shrimp and blue whales add to the clamor by emitting a barrage of signals, in large part because sound propagates well in the sea and provides a good channel for communication (Urick 1983). Many of these animals depend on receiving acoustic signals, their own or those of others, to capture prey or avoid predators, reproduce, and navigate (Myrberg 1980, 1990). Noise may interfere with life in the sea and these vital processes.

Most underwater noise made by humans, and especially most of the noise propagating long distances, is low frequency sound below 1000 Hz (LFS). Marine animals may be affected by noise generated nearby, such as a ship passing overhead, or by distant sources. LFS from strong sources can travel up to 20,000 km in the deep sound channel or SOFAR channel (Munk *et al.* 1988). The axis of this channel, where transmission loss is minimal, varies from 1200 m deep in midlatitudes to near the surface in polar waters (Urick 1983). Thus, in temperate zones, marine mammals whose calls and hearing are below 1000 Hz, and that dive deeply, might be particularly affected by LFS generated by human activities.

The aim of this project was to record sounds impinging on free-ranging northern elephant seals, *Mirounga angustirostris*, a first step in determining the importance of LFS to these animals as they dive, forage and migrate to and from their rookeries in the eastern north Pacific Ocean.

Three characteristics of elephant seals - their apparent low frequency hearing range, deep diving, and foraging proximity to ship traffic - led us to reason that they may be vulnerable to interference by LFS:

1) Males emit airborne low frequency sounds with a fundamental frequency of about 175 ± 30 Hz in air (Le Boeuf and Petrinovich 1974), so we assume that they hear these sounds and that these sounds convey important information. Anatomical studies of the cochlea of elephant seals are consistent with sensitivity to low frequencies (Ketten 1995). The underwater hearing threshold for one juvenile was measured as 90 dB re 1 μPa at 100 Hz (Kastak and Schusterman 1995).

2) When at sea, the elephant seal spends as much time submerged as do most whales and is one of the few marine mammals that dives into the deep sound channel. For example, adult females spend 83% of the year at sea, 90% of it submerged; both sexes dive to mean depths of 500 m and maximum depths of 1500 m (Le Boeuf *et al.* 1988; DeLong and Stewart 1991; Le Boeuf 1994).

3) The migratory paths of all major age groups of both sexes traverse zones in the northeastern Pacific ocean (Le Boeuf *et al.* 1993; Le Boeuf 1994; Stewart and DeLong 1994) that sustain heavy ship traffic year round.

There are practical advantages for acoustic monitoring of elephant seals compared to other marine mammals. Their large size permits them to carry large instrument packages. These packages can be both attached and recovered when the animals are on land. Strong ties to the rookery for seals one year or older insure an instrument recovery rate of 90-95%. Behavioral and physiological responses to sound can also be determined in short term translocation experiments of a few days or long term studies during natural migrations lasting several months (Le Boeuf 1994).

The specific aims of this research were to determine whether free-ranging, diving elephant seals actively produce sound, the predominant frequencies and sound levels impinging on them, the dive pattern during acoustic recording, and the best attachment, shape and location of the instrument package for minimizing flow noise. We wanted to obtain fundamental information on the sound field to which elephant seals are exposed as an aid in designing and programming large capacity dataloggers for long-term deployments during migration.

I. METHODS

A. Subjects, site and general approach

Six juvenile elephant seals, one male and five females, 1.4 to 1.8 years old and weighing 148 to 211 kg, were captured while resting on the rookery at Año Nuevo State Reserve, California. An instrument package containing an acoustic recorder and a dive recorder was glued to the backs of the seals (Le Boeuf *et al.* 1988) and they were translocated to Monterey Bay and released over deep water (Le Boeuf 1994), 18 km from shore and 35 km south of Año Nuevo (Table 1; Figure 1). The seals returned "home" to the rookery within seven days of release and were recaptured; the instrument packages were removed and the acoustic and dive data were analyzed.

The experiment was conducted in stages. In the spring and fall of 1994, acoustic packages were deployed on three seals. Captive studies in the laboratory were performed in spring, 1995. Information gathered from these initial studies, and from a captive animal study conducted in the winter of 1995, led to improvements in method that reduced extraneous noise and enhanced the clarity of recordings obtained in three deployments in spring of 1995.

B. Instrument package

The seals carried instruments for recording sound, swim speed, the depths and durations of dives, and the time of return to the capture site (Table 1).

1. Acoustic recording

The acoustic unit consisted of a Sony TCD-D7 digital audio tape (DAT) recorder (frequency response 20-14,500 Hz; 32 kHz sampling rate) enclosed in an aluminum housing measuring 17.08 x 12.70 x 6.67 cm that was pressure tested to 800 m. The acoustic unit used for the first three deployments weighed 5.6 kg in air, but was positively buoyant in water. The acoustic unit used for the last three deployments weighed 2.9 kg in air and was slightly negatively buoyant. The hydrophone (High Tech, Inc. HTI-SSQ-41B) used on the last three deployments had a sensitivity of -168 dB re 1V/μPa and a frequency range of 10 Hz to 30 kHz. During the last four deployments, the right channel recorded the full bandwidth of the DAT recorder and the left channel of the recorder had a high-pass roll off frequency of 50 Hz to avoid saturation of this channel from strong low frequency noise. A circuit was designed to initiate DAT recording just prior to release (Fletcher 1996).

2. Diving pattern

In addition to the acoustic package, four seals carried a time depth recorder, the Mk3 (Wildlife Computers, Redmond, WA), a microcomputer with 256 kb RAM programmed to sample depth and ambient temperature at 5 s intervals. A two stage pressure transducer measured depth to 2,000 m (accurate to within 2 m above 450 m and 10 m below 450 m). Depth and temperature data were stored in memory with reference to an internal electronic clock. The dive recorder was encased in a tubular titanium housing, measuring 15.4 X 2.9 cm and weighing 196 g.

One seal carried a custom made swim speed-time-depth recorder that measured 6.5 x 3 x 15 cm, weighed 450 g, and incorporated a Tattletale Fast Lite datalogger, model L-512psf (Onset Computer Corp., Pocasset, MA). The instrument has 512 kb RAM and was programmed to sample diving depth and swim speed every 5 s. Diving depth was measured with a Keller pressure transducer (model PA-7-100, KPSI, Oceanside, CA) calibrated between 0 and 1000 m before deployment; error was estimated at $\pm$ 2.5 m. Swim speed was obtained by counting and storing in memory the revolutions of a Logtron paddle wheel (Flash Electronic GMBH, Dachau, Germany).

Swim speed was calibrated using a method suggested by Michael Fedak (Fedak 1993). We matched the animal's rate of change in depth with the corresponding number of paddle wheel revolutions (Fig. 2). The rate of change in depth, or vertical speed, was calculated every 15 s from the pressure transducer's depth readings. This was plotted against the total number of paddle wheel revolutions during the same 15 s, expressed as revolutions per minute (RPMs). There are many possible RPM values for each vertical speed, each corresponding to a different angle of ascent or descent. The high RPM values reflect shallow dive angles (the seal is swimming fast but changing depth slowly). Low RPM values reflect steep dive angles, i.e., approaching vertical dives. We assumed that the lowest RPM values at each descent or ascent rate reflect vertical dives in which swim speed equaled the rate of change in depth. This assumption was used to generate the calibration line, a regression line through the lowest RPM values at each vertical speed above 0.22 m/s, the stall speed of the instrument determined experimentally.

3. Location

All seals carried radio transmitters (Advanced Telemetry Systems, Inc., Isanti, Minnesota) hose-clamped to the diving instrument to aid in locating the seal with a radio receiver (Telonics, Mesa, Arizona) when it returned to the rookery. In addition, four seals carried Argos satellite tags (Model ST-6; Telonics Inc, Mesa AZ) attached either to the neoprene patch or to the pelage on the head with marine epoxy (Evercoat Ten-set, Fibre-Evercoat Co., Cincinnati, Ohio), which revealed the time that the seals returned to Año

Nuevo. The satellite tags had dimensions of 6.5 x 14 x 4.5 cm, weighed 490 g in air and 130 g in sea water.

C. Captive animal preliminary study

In winter of 1995, experiments were conducted in a salt water tank (16.5 m long X 12.2 m wide X 2.7 m high) at the Long Marine Laboratory to determine the appropriate recorder gain setting for the DAT on free-ranging seals and whether to encase the hydrophone in potting compound. The acoustic package was harnessed to a captive adult male California sea lion, *Zalophus californianus*, that swam freely in the tank in company with another sea lion and two bottlenose dolphins. Since sea lions swim more rapidly in a small pool than captive elephant seals, they provided a greater range of flow noise and a better test. The hydrophone was placed in several different positions during trials, the gain was varied, and flow noise was compared with and without encasing the hydrophone directly to the lid of the housing with GE RTV615 silicone potting compound.

D. Field capture, instrument attachment, release and recovery

All seals were chemically immobilized with Telazol (Aveco Co. Ltd., Fort Dodge, Iowa) and ketamine hydrochloride (Briggs *et al.* 1975). After measurement and weighing (Le Boeuf *et al.* 1988), they were placed in a cage and transported to the Long Marine Laboratory where a neoprene patch (0.5 X 0.4 m) was glued to the pelage on the seal's back with neoprene rubber cement (Fletcher 1996). The following morning all instruments (acoustic package, TDRs, radiotransmitters, and three satellite tags) were fastened to D rings on the neoprene patch on the seal's back. One satellite tag was glued to the top of the head with marine epoxy. In an attempt to achieve neutral buoyancy and to improve hydrodynamics, syntactic foam was placed around the acoustic package on the first three seals tested.

The instrumented seal was released the day after initial capture. It was put into a travel cage, loaded onto a truck, and transported to a boat at Moss Landing harbor. The boat reached the release site (Fig 1) approximately two hours after departing the harbor. After the DAT was started, the door to the seal's cage was opened and the seal dove into the water.

When satellite tags or daily surveys with a radio receiver indicated that a seal had returned to Año Nuevo (Fig. 1), we recaptured the seal and recovered the instruments. In spring, the seals molted, discarding the neoprene patches that had held the instruments.

E. Data analysis

Detailed analyses of the acoustic record were conducted using Canary bioacoustics software (Cornell University, Ithaca, NY). All spectrum analyses were conducted with the following settings: filter bandwidth = 87.42 Hz, frame length = 1024 Hz, frequency bin = 21.53 Hz, FFT length = 1024 points. Spectrogram settings were adjusted to optimize the image for each particular sound. Sound levels received on the seals were determined from a calibration signal placed at the beginning of each tape (100 mV peak to peak at 500 Hz) and from the manufacturer specified hydrophone sensitivity.

In order to evaluate the effects of swim speed on flow noise, we scanned the swim speed records for 18 segments at intervals from 0 m/s to 1.8 m/s. We then selected 5 s sound segments associated with each speed. Acoustic records were selected for not containing strong signals from external sources such as ships. Canary was used to calculate the spectrum of each noise sample, and we extracted the spectrum level at 50, 100, 200, 300, and 400 Hz.

Two different methods were used to measure the level of transient noises. For impulsive sounds, we selected segments that included most of the impulse energy, and from them calculated the mean broadband pulse sound pressure level. For more continuous vessel noise, we located the frequency with the peak spectrum level and measured the bandwidth of the vessel noise 3 dB down from each side of the spectral peak.

The Wildlife Computer dive analysis program was used to compute summary dive statistics. Axum (Trimetrix, Seattle, WA) was used to calibrate swim speed.

We set an alpha level of 0.05 for all statistical tests. Variation around means are presented as ± one standard deviation.

II. RESULTS

A. Fall 1994 deployments

No acoustic data were obtained from two of the three initial deployments in 1994 (Table 1). The salt water switch failed to initiate the tape recorder carried by 94A although a complete diving record was obtained. Seal 94C did not return to Año Nuevo; the satellite tag on its head stopped giving locations after two days. A full 3-hour tape recording was obtained for seal 94B, as well as a complete diving record. Cable strum, however, produced excessive background flow noise, effectively masking other acoustic data.

It was clear from these initial deployments that the housing was water-proof, seals could be expected to return to the rookery within six days, and a simultaneous diving and acoustic record could be obtained. Modifications in the procedure were required, however, to improve the acoustic recordings. The gain setting needed to be optimized and cable strum noise needed to be eliminated. Tests in the laboratory with the acoustic package harnessed to a sea lion showed that cable strum could be avoided and flow noise decreased by potting the cable and hydrophone to the housing cap. The gain was adjusted so that saturation did not occur on either channel. The syntactic foam coverings on the instrument package were eliminated for the 1995 deployments.

B. Spring 1995 deployments

High quality acoustic recordings, each lasting 3 hours, were obtained from the instruments deployed on all three seals in spring 1995. In addition, a time-linked diving record was obtained for seal 95B, and a time-linked diving and swim speed record was obtained for seal 95C. The TDR on seal 95A did not function. The remainder of this paper examines data collected from these three seals.

1. Diving pattern

The diving pattern of the seals from the time of release until the acoustic records ended three hours later reflects the continuous, deep, long duration diving that is characteristic of elephant seals (Table 2). The mean dive depth, mean dive duration, mean surface interval and percent time at the surface (± one standard deviation) are not significantly different from mean values obtained from nine free-ranging, 1.4 year olds during their five month foraging period at sea, 328 ± 44 m, 13.3 ± 1.0 min, 2.04 ± 0.6 min, and 12.3 ± 3.1 %, respectively (Le Boeuf *et al.* 1996). This suggests that the diving pattern of the subjects was normal and that the instrument package did not cause significant impediment to diving. It is also clear from the depths of dives that throughout the acoustic recording period the seals were in water deeper than 140 m, i.e., off the continental shelf.

2. *Flow noise*

With the hydrophone facing the seal's head (seal 95A), flow noise sounded like the seal was in a wind tunnel. By orienting the hydrophone to the animal's rear (seals 95B and 95C), flow noise was reduced significantly within the range 20-400 Hz (Fig. 3).

Flow noise varied as a function of swim speed and frequency. We extracted 18 five second samples of flow noise at a range of swim speeds in order to evaluate flow noise in frequencies ranging from 50 to 400 Hz. Flow noise was greatest at 50 Hz and ranged from 88.6 to 108.1 dB re 1 $\mu Pa^2/Hz$ for seal 95C (Fig. 4). It was variable during the course of diving because flow noise increased with swim speed. In order to evaluate the relation between swim speed and dive depth, we extracted all speed and depth data from the dive record of 95C, excluding surface intervals (Fig. 5). Swim speed was 17% higher during descent and ascent than during the remainder of the dive. Swim speed was lowest when the seal was at the bottom of a dive, which took up approximately 40% of total dive duration. At times, swimming stopped altogether (Fig. 6). Since flow noise was positively correlated with swim speed, flow noise was lowest during the bottom portions of dives.

How significant was flow noise? Flow noise was greatest at low frequencies; levels at 50 Hz were consistently higher than at frequencies up to 400 Hz (Fig. 3). At modal swim speeds of 1.1 m/s, with the hydrophone oriented toward the rear of the seal, the mean level of flow noise at 100 Hz was 81 dB re 1 $u\mathrm{Pa}^2/\mathrm{Hz}$, low enough that we were able to detect many transient sounds. This level is similar to the auditory sensitivity of a juvenile elephant seal tested at this frequency (Kastak and Schusterman 1995). To make the spectrum level of noise in a 1 Hz bandwidth comparable with seal hearing, however, we must correct for the bandwidth of seal hearing at each frequency. The ratio of the strength of a pure tone signal to the spectrum level of broadband noise, the critical ratio, is not known for elephant seals but is close to 20 dB at these low frequencies. Adding 20 dB to the figures in Figure 3, for a swimming seal with the hydrophone oriented backward, yields 101 dB at 100 Hz, 96 dB at 200 Hz and 85 dB at 400 Hz. This is only marginally higher than thresholds measured from a stationary juvenile seal by Kastak and Schusterman (1995): 90 dB at 100 Hz, 73 dB at 200 Hz and 76 dB at 400 Hz. This comparison shows that we minimized flow noise on our recorders to insignificant levels during normal swimming and that flow noise was absent when the seal stopped the dive record of 95C, excluding surface intervals (Fig. 5). Swim speed was 17% higher during descent and ascent than during the remainder of the dive. Swim speed was lowest when the seal was at the bottom of a dive, which took up approximately 40% of total dive duration. At times, swimming stopped altogether (Fig. 6). Since flow noise was positively correlated with swim speed, flow noise was lowest during the bottom portions of dives.

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3. Ambient noise

Dominant frequencies of ambient noise measured on each seal during all phases of diving were in the range, 20-200 Hz.

Many transient signals from distant sources are clearly audible in the records. We identified signals that sound like those from snapping shrimp, cetacean vocalizations, small explosive charges, and boat noise. The cetacean vocalizations illustrated in Figure 7 represent numerous dolphins but we could not identify the species. A total of three short duration impulsive sounds of approximately 250 ms were audible in the records of seals 95A and 95B. The average pulse pressure level of the impulse in 95A's record was 116 dB re 1 μPa. The depth of the seal at the time of the detonation is not known. Dolphin vocalizations in the background ceased for 820 milliseconds following the explosion and then reverted to pre-explosion levels for 1.45 seconds (Fig. 7). Two impulses were audible in 95B's record. The received sound levels were 118 and 129 dB re 1 μPa at depths of 320 and 304 m, respectively. These impulses did not cause obvious changes in the diving behavior of this seal (Fig. 8). One common source of impulses of the kind recorded here are "seal bombs" which fishermen use to keep seals away from fishing operations (Awbrey and Thomas 1987).

Boat noise from the release vessel was evident for approximately 10 min after the seal was released. Other vessel noises were evident 5 times in the three records for a total duration of 130 minutes (23.5% of the total time recorded). The most intense vessel noise occurred when seal 95B was at 430 m on a dive to 463 m (Fig. 8, 9). This vessel noise had a broadband average sound pressure level of 119 dB re 1 μPa and was greatest at the lowest frequency recorded by the DAT. At the 20 Hz low frequency cutoff, the spectrum level was 105 dB re 1 $\mu Pa^2/Hz$. This spectrum level slowly decreased with increasing frequency, with a 3 dB point (halving of level) at 29 Hz. Figure 8 illustrates the dive behavior of this seal during vessel approach, when the two impulses were recorded. Assuming spherical spreading and the boat directly overhead, this is roughly equivalent to a broadband source level near 172 dB re 1 μPa at 1 m. If the boat was not directly overhead, the source level would have been even higher. This was the deepest of 129 dives made by this seal during its time at sea, but more deployments will be required to assess whether this represents a coincidence or a predictable dive response to vessel noise. The noise from this boat was audible for over 44 minutes. Other than the depth of this dive, boat noise did not seem to alter the diving behavior of this seal (Fig. 8) or seal 95C (Fig. 10).

4. Ambient LFS and depth

In order to examine the relationship between depth and ambient noise, we selected 19 tape segments for seal 95B and 17 tape segments for seal 95C at times corresponding to different depths. We listened to each tape segment and selected four to five sounds with minimal flow noise. LFS in Monterey Bay, as recorded on seals 95B and 95C, did not vary significantly with dive depth to 400 m (Fig. 11).

5. Sounds originating from the seals

We listened to all acoustic records several times. We did not discern any active calls or vocalizations that resembled elephant seal calls in air. Given the flow noise averaging 60 - 100 dB re 1 $\mu Pa^2/Hz$, depending upon frequency and swim speed, we would have been likely to detect calls if the seals had emitted any.

The beginning and end of a surface interval between dives could be determined from the abrupt cessation of flow noise, water lapping against the hydrophone, and other surface sounds. This was confirmed by the close match obtained between surface interval durations determined from the acoustic recordings and those determined from the time-depth recorders. During all surface intervals and at no other time, we recorded signals that sounded like breathing. We confirmed that these breathing sounds were correctly identified by analyzing video and acoustic records of a juvenile's post-dive respiratory pattern in a 2.5 x 2.5 x 1.2 m salt water tank at the Long Marine Laboratory. Sounds of breathing were tightly synchronized with the animal opening and closing its nostrils. During silent intervals at the surface, we also heard sounds like heart beats heard with a stethoscope. Respiration sounds and these putative heart beats at the surface between dives were strong enough to be counted during all surface intervals of all three seals (Fig. 12). The mean respiratory rate per seal ranged from 22 to 24.6 breaths per min and the mean putative heart rate per seal ranged from 117 to 121.6 beats per min (Table 2). These putative heart rate sounds occurred at a rate similar to heart rates estimated from EKG records of free ranging and captive juvenile elephant seals (Webb 1995). In order to evaluate the relationship between breathing rate and putative heart rate at the surface, we averaged breathing and putative heart rates for each surfacing. There was a positive correlation between breathing rate and putative heart rate for all seals: 95A ($r_{12\ samples}$ = 0.717, two-tailed test, $P < 0.05$), 95B ($r_{9\ samples}$ = 0.390, two-tailed test, $P > 0.05$) and 95C ($r_{10\ samples}$ = 0.578, two-tailed test, $P < 0.05$).

6. Swim strokes

At the beginning of descent and especially at the end of ascent, when swim speed was highest, we also heard a rhythmic variation in flow noise that seemed to be associated with swim strokes made by a sculling action of the hindflippers (Fig. 13). The acoustic energy of this signal was concentrated between 20 and 400 Hz and often extended above 1000 Hz. On average, the putative stroke rate of the three seals ascending in the top 100 m of water to the surface was 120 strokes/min and sometimes as high as 145 strokes/min. This stroke rate is similar to the fastest rate, 135 strokes/min, recorded from a free-swimming juvenile by means of a video camera attached to its back, oriented towards its hindquarters (Davis *et al.* 1993).

III. DISCUSSION AND CONCLUSIONS

This study shows that it is feasible to record acoustic signatures received on a diving seal in its natural environment simultaneous with recording diving performance and concomitant physiological variables such as respiration and heart rate. Flow noise was less of a problem that we anticipated. Although the levels obtained in the last two deployments are acceptable, further reductions can be obtained by reducing the size of the instrument package and improving its hydrodynamics.

On the practical side, the data obtained in this study provide essential information for designing and programming a high capacity acoustic datalogger for use in sampling the sound field of the elephant seal during its biannual migrations in the northeastern Pacific. Integration of dive and swim speed with acoustic data in such a logger would allow more sophisticated data sampling strategies. For example, elephant seals stop swimming during the course of some dives. This study showed that flow noise could be dramatically reduced and recording duration increased by storing acoustic data at times with slow swimming speeds. Longer term deployments should reveal whether elephant seals change their behavior or avoid areas where LFS is high, such as near shipping lanes. In addition, tracking of acoustically instrumented seals near fixed sound sources should reveal the time sequences of the levels of the sounds received on the seals and the reactions of the seals to the sound stimulus.

An unexpected and valuable product of onboard acoustic recording is acquisition of respiratory rate and heart rate at the surface between dives. This provides a simple and valuable tool for studying the diving process. Analysis of the relationship between these physiological events at the surface and preceding or succeeding dive depth, dive duration and swim speed can reveal the speed of recovery from diving effort or anticipation of diving effort. Respiratory rate at the surface between dives has not been measured previously in free-swimming elephant seals or any other pinniped. The respiratory rates obtained in this study are 2.7 to 2.9 times faster than those recorded from seals on land between bouts of sleep apnea (Blackwell and Le Boeuf 1993); a disparity that is explained in large part by the difference in exercise. The heart rates recorded at the surface in this study are similar to those recorded in juvenile elephant seals of the same age in nature (Andrews *et al.* 1991) and in the lab (Webb 1995) using Holter monitors or heart rate transmitters. The latter methods are unreliable, however, because sea water often shorts out the surface electrodes attached to the seal's skin. The acoustic method of recording heart rate may prove more reliable. Lastly, a fuller understanding of cardiac function during diving might be obtained by acoustic measurement of heart rate during certain segments of diving. This is feasible using signal processing, but a demonstration of this technique is beyond the scope this paper.

It is not clear from this preliminary analysis whether diving elephant seals are adversely affected by boat noise or noise pulses from distant detonations. A comparison of the timing of these sounds and the general diving pattern suggests a potential association of the deepest dive with the loudest vessel approach, but given the variability observed in diving behavior, many more deployments will be required to resolve these issues. Future studies will require a more detailed analysis of this potential effect and examination of variables such as changes in heart rate or swim speed.

We conclude that onboard acoustic recording is a promising new tool for understanding a marine mammal's response to LFS. Although the instrument package was large for attachment to most other marine mammal species, we anticipate that later versions can be significantly reduced in volume and weight.

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LEGENDS TO FIGURES

1. A bathymetric map of central California showing the relationship between the capture site of juvenile elephant seals (Año Nuevo rookery), the intermediate overnight site where the instrument package was attached (Long Marine Laboratory), ports from which the seals were translocated to sea (Santa Cruz, Moss Landing), and the release sites in Monterey Bay (open circle). The continental shelf break is indicated by the 200 m contour.

2. Calibration of swim speed for the instrument carried by seal 95C was obtained by plotting a linear regression line through the lowest RPM values of the paddle wheel at each vertical speed sampled (filled triangles) above 0.22 m/s (filled circle), the stall speed of the instrument. This calibration assumes that the lowest RPM values at each descent rate reflect vertical dives in which swim speed equaled the rate of change in depth.

3. Flow noise decreased during swimming (filled circles) with a change in the orientation of the hydrophone on the seal's back from facing forward (left figure, seal 95A) to facing backward (right figure, seal 95C). Flow noise was reduced to presumed ambient noise levels when the seals stopped swimming (open circles).

4. Flow noise at 50, 100, 200, 300 and 400 Hz as a function of swim speed for seal 95C. See text for method of calculation.

5. A scatter plot showing swim speed as a function of dive depth for seal 95C.

6. A schematic representation of a single dive of seal 95C showing swim speed and depth versus time. The dotted line shows a period when the seal stopped swimming and flow noise was reduced.

7. Spectrogram of cetacean vocalizations preceding and succeeding an impulsive signal apparently produced by a small explosion.

8. Tracings from a segment of the dive record of seal 95B in which time with boat noise (horizontal black line) and small explosions (arrows), possibly seal bombs, are shown.

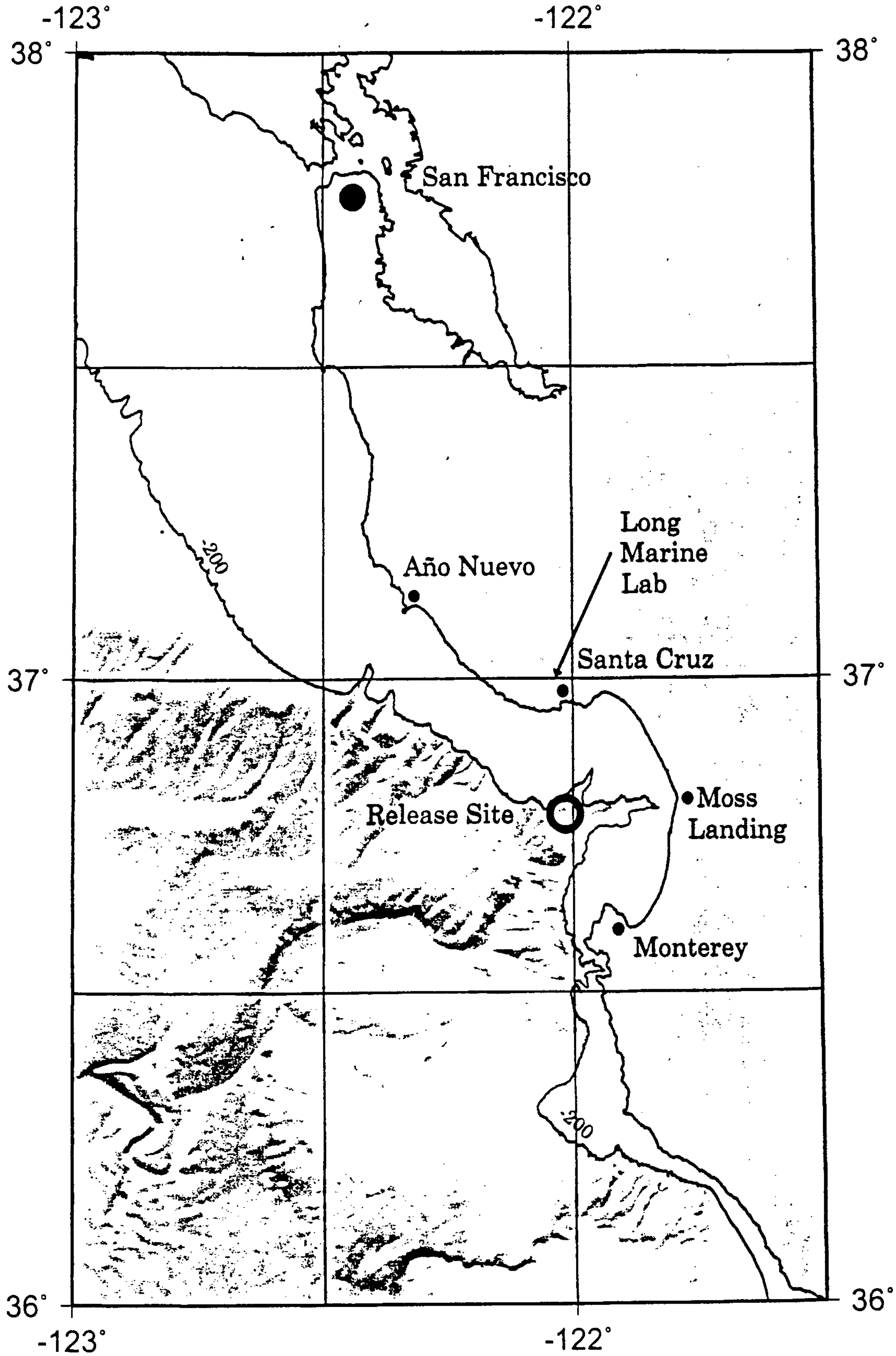
9. Spectrogram of boat noise received by seal 95B at 430 meters.

10. Tracings from a segment of the dive record of seal 95C showing dive depth and swim speed in relation to boat noise (horizontal black line).

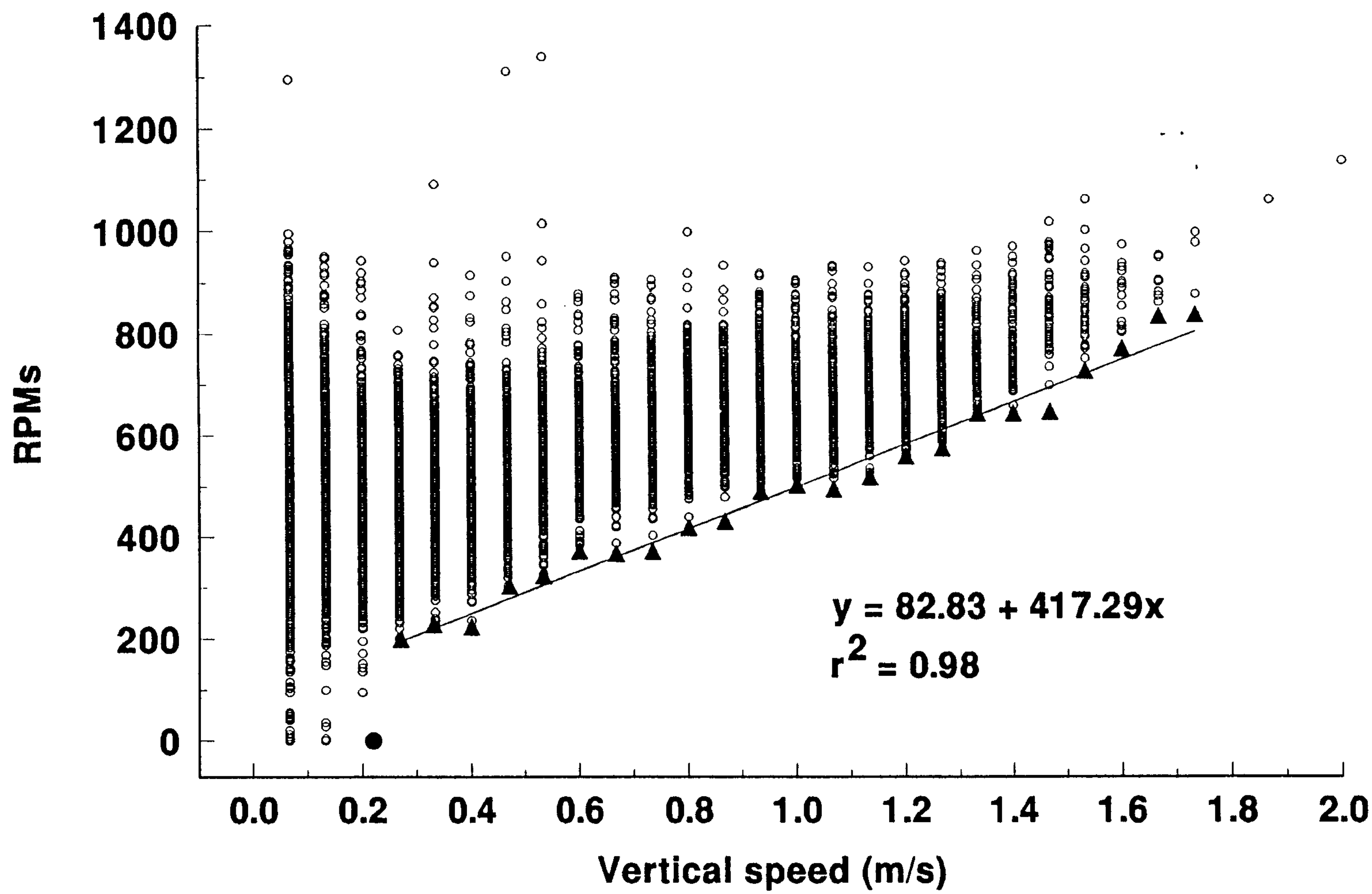
11. Ambient noise at 50, 100, 200, 300 and 400 Hz as a function of depth for seal 95B (upper figure) and seal 95C (lower figure).

12. Spectrogram and waveform from the acoustic record of seal 95C depicting two respiratory events and putative heart beats at the surface between dives. Putative heart beats in this sample are every two seconds, yielding a putative heart rate of 120 beats per minute.

13. Spectrogram from the acoustic recording of seal 95C showing eight putative swim strokes during ascent. The putative stroke rate is approximately 2.4 strokes/s. The source of the broad frequency event at 3.5 s is unknown but appears to be a signal from snapping shrimp.

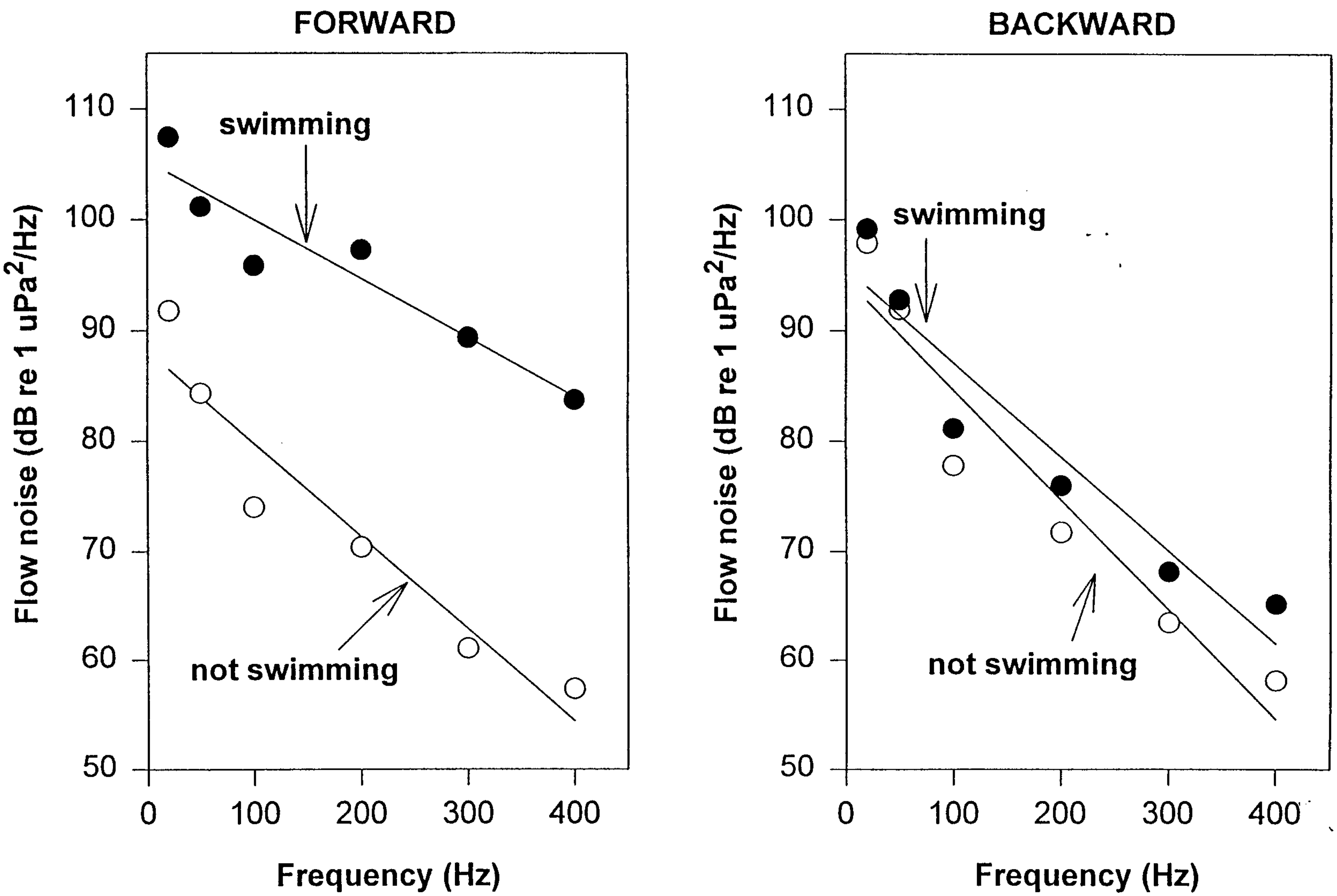


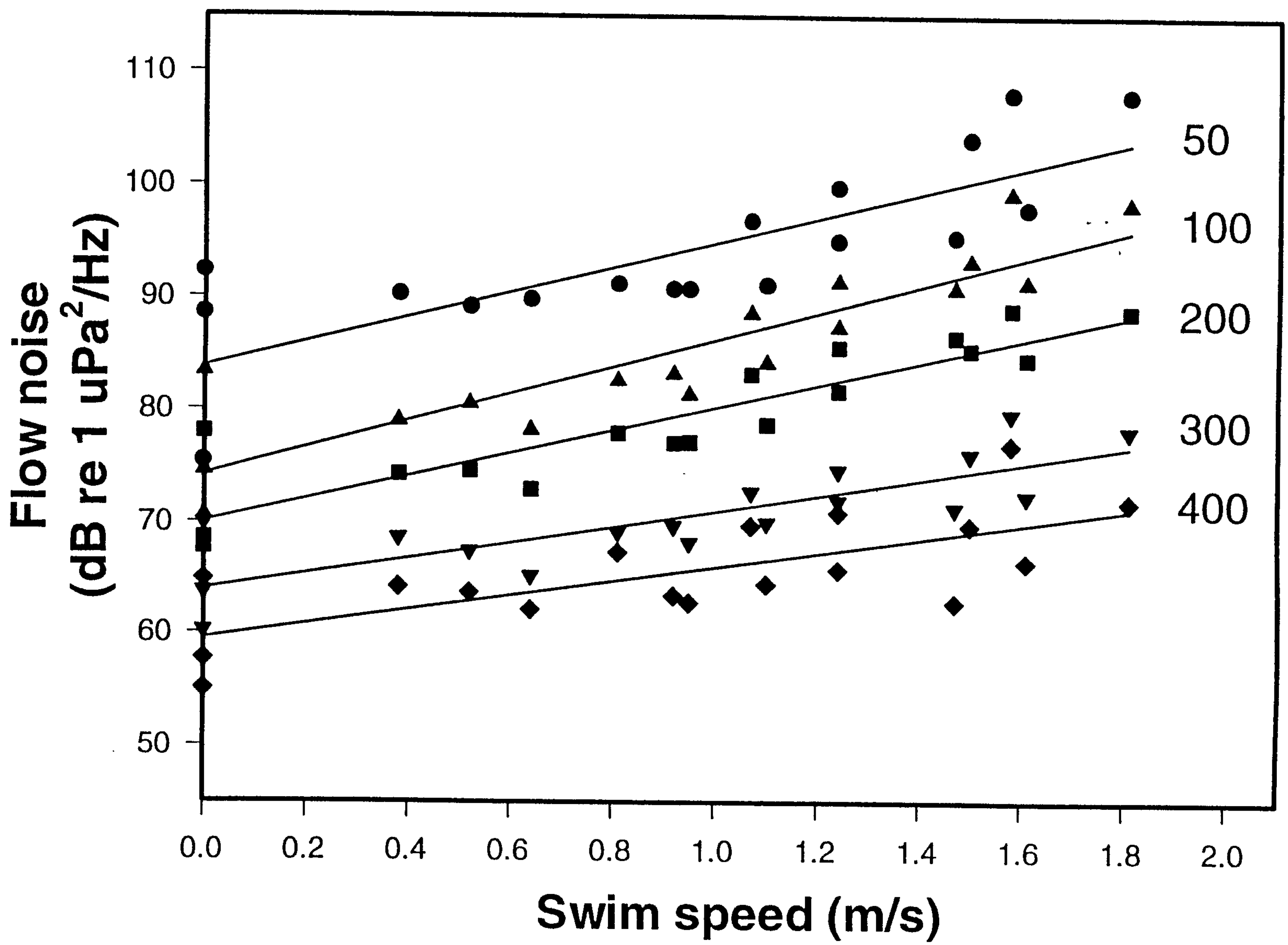
-123°
-122°
38°
38°
San Francisco
-200
Año Nuevo
Long
Marine
Lab
Santa Cruz
37°
37°
Release Site
Moss
Landing
Monterey
-200
36°
36°
-123°
-122°



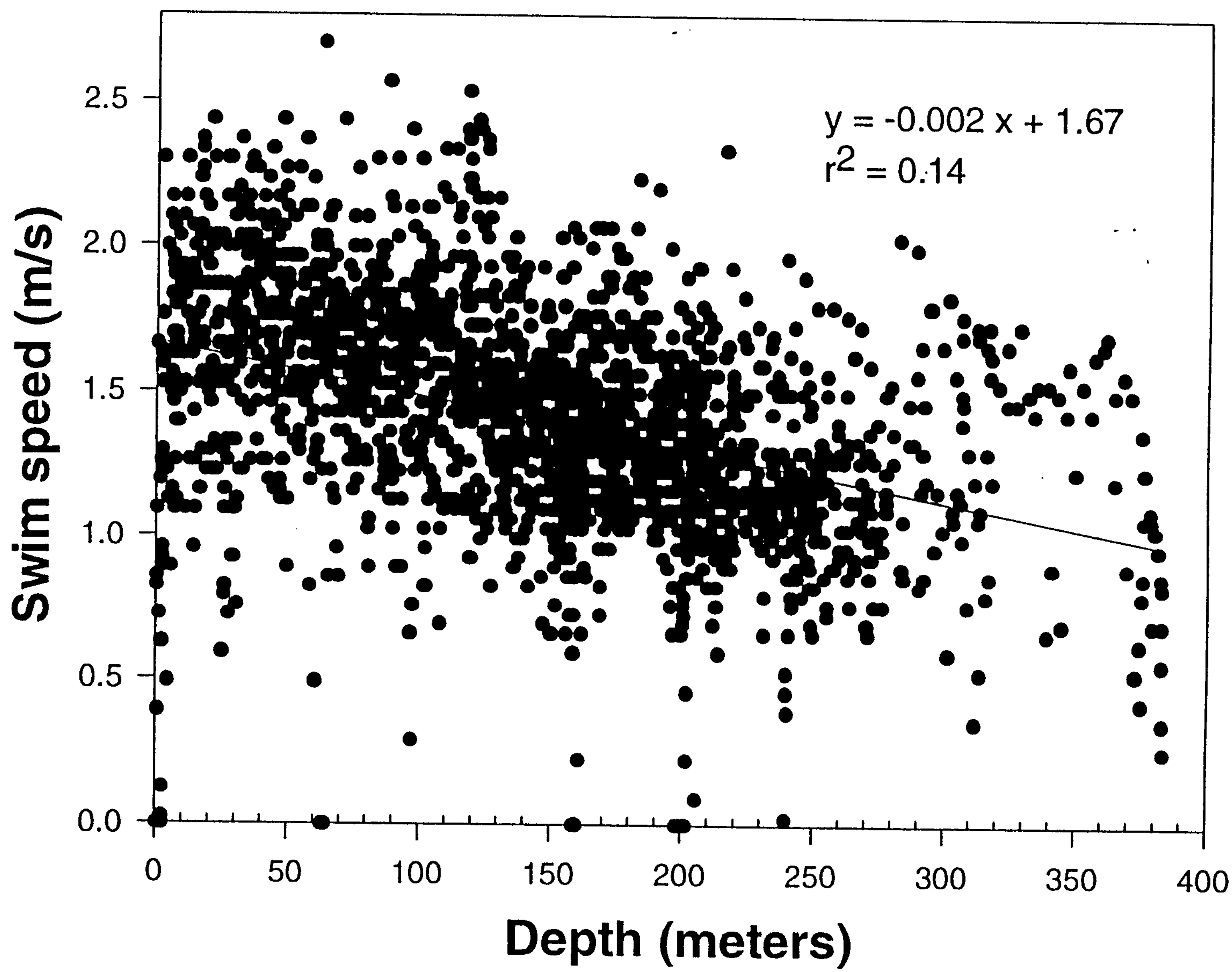
1400
1200
1000
800
600
400
200
0
RPMs
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Vertical speed (m/s)
y = 82.83 + 417.29x
r2 = 0.98

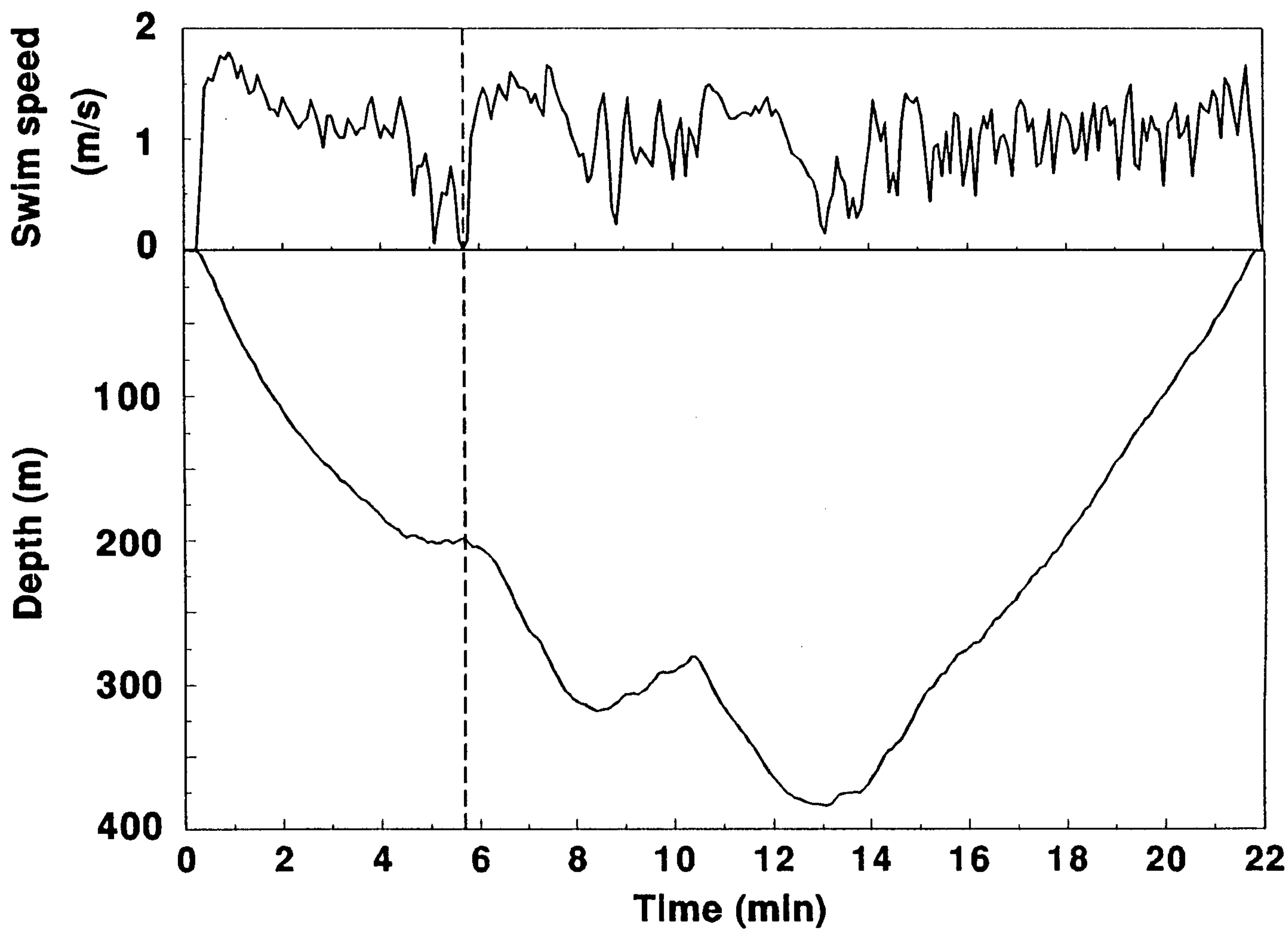
HYDROPHONE ORIENTATION



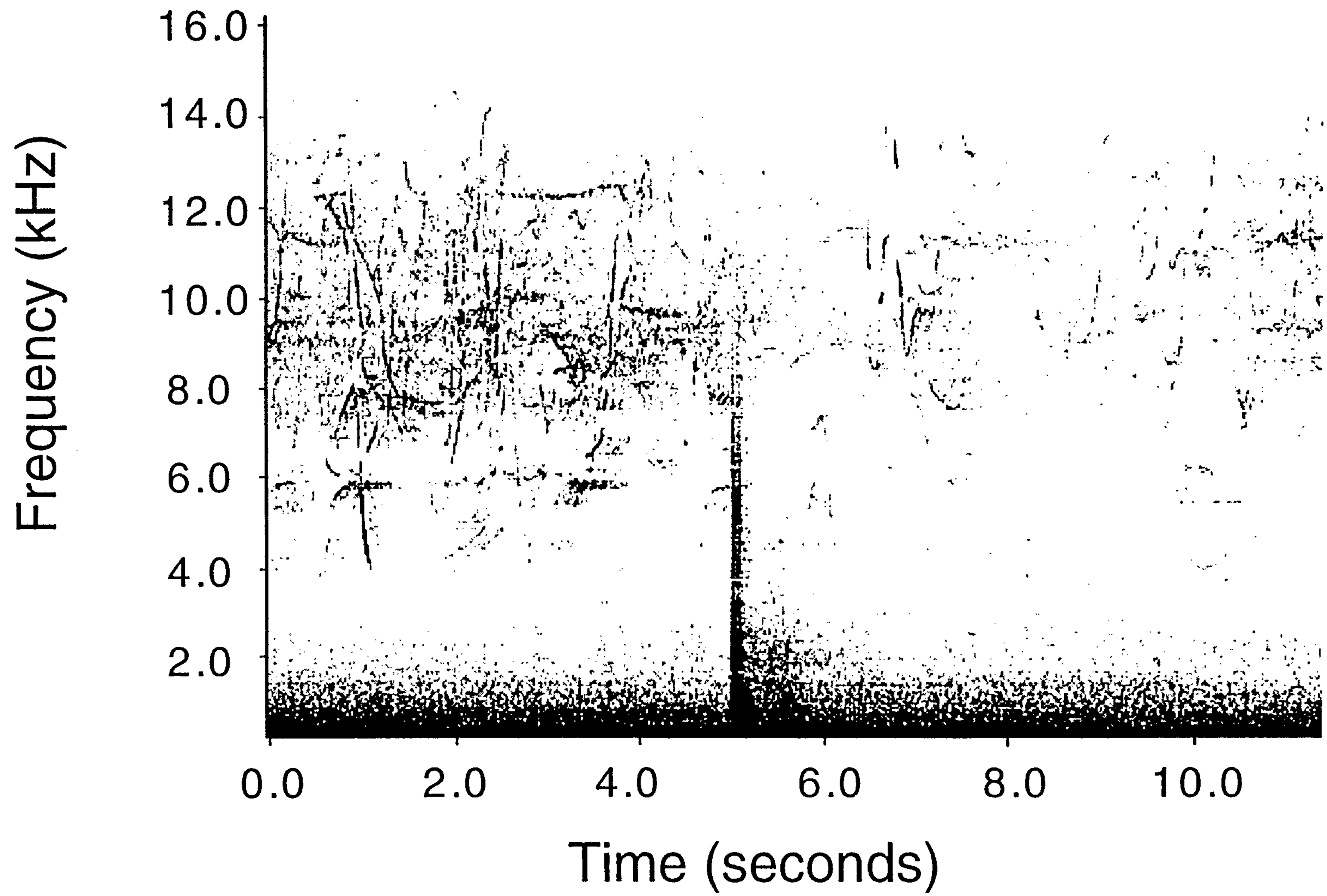


Flow noise
(dB re 1 uPa²/Hz)
110
100
90
80
70
60
50
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Swim speed (m/s)
50
100
200
300
400

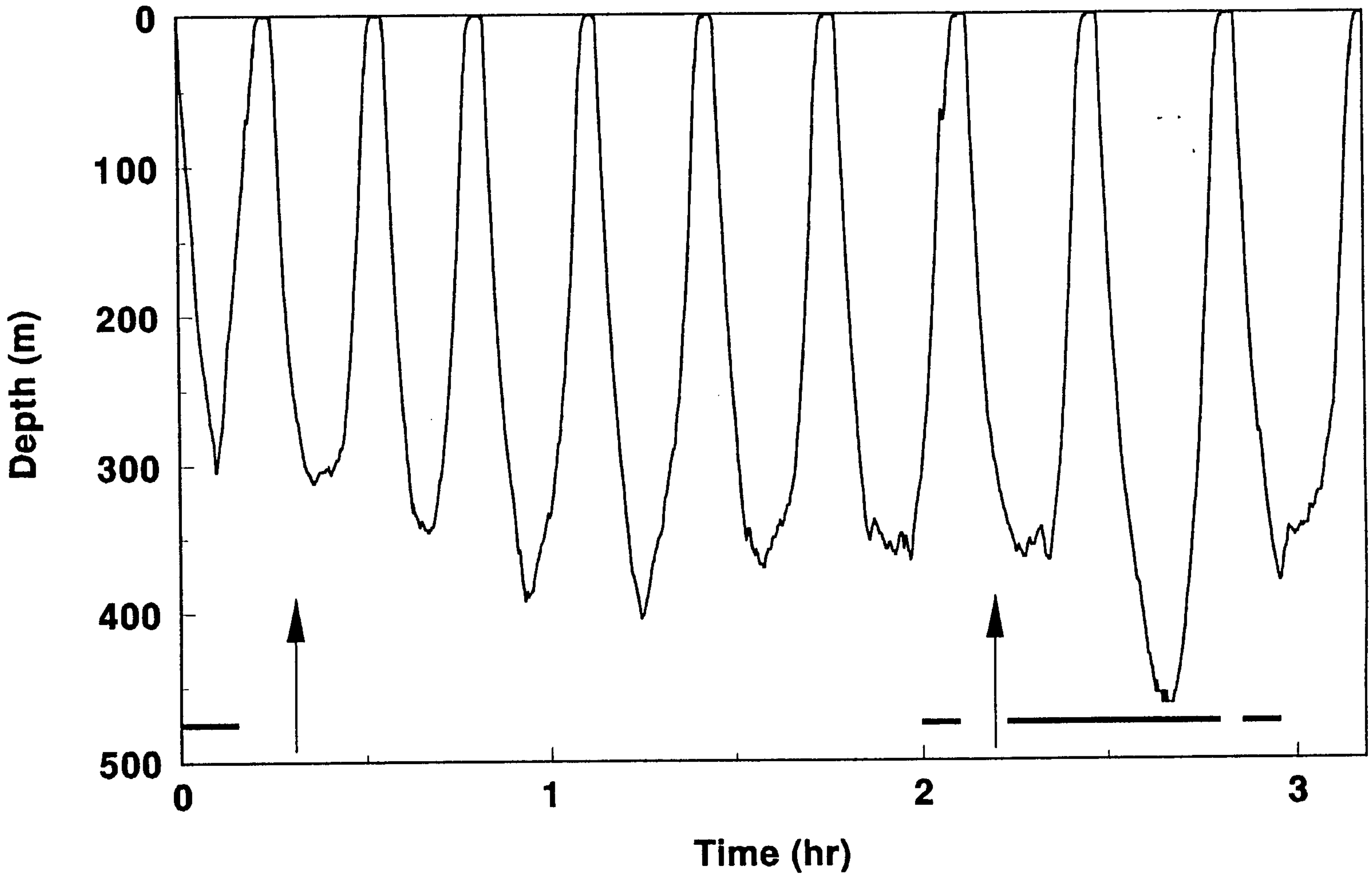

y = -0.002 x + 1.67
r^2 = 0.14
Swim speed (m/s)
0.0
0.5
1.0
1.5
2.0
2.5
0
50
100
150
200
250
300
350
400
Depth (meters)

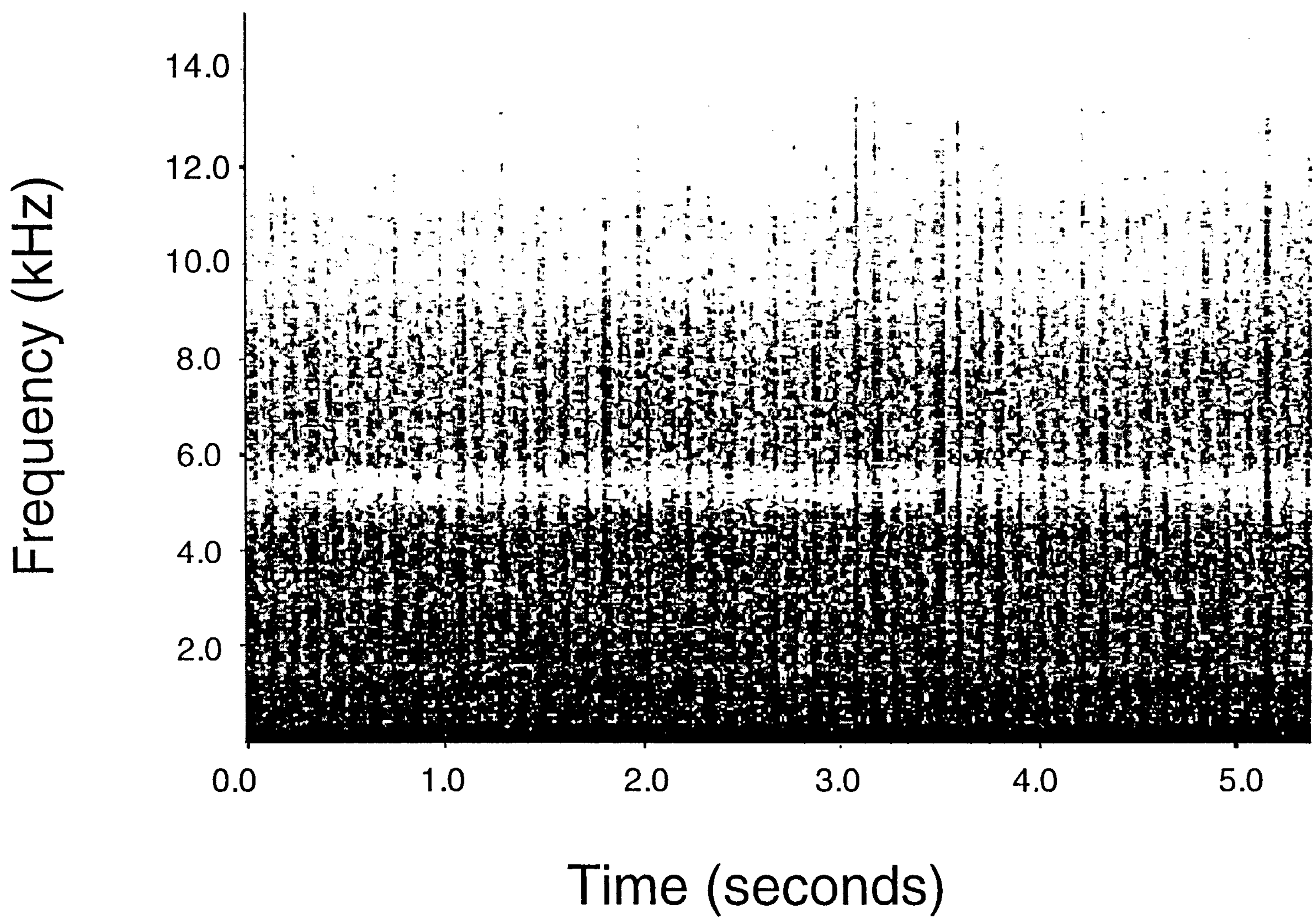


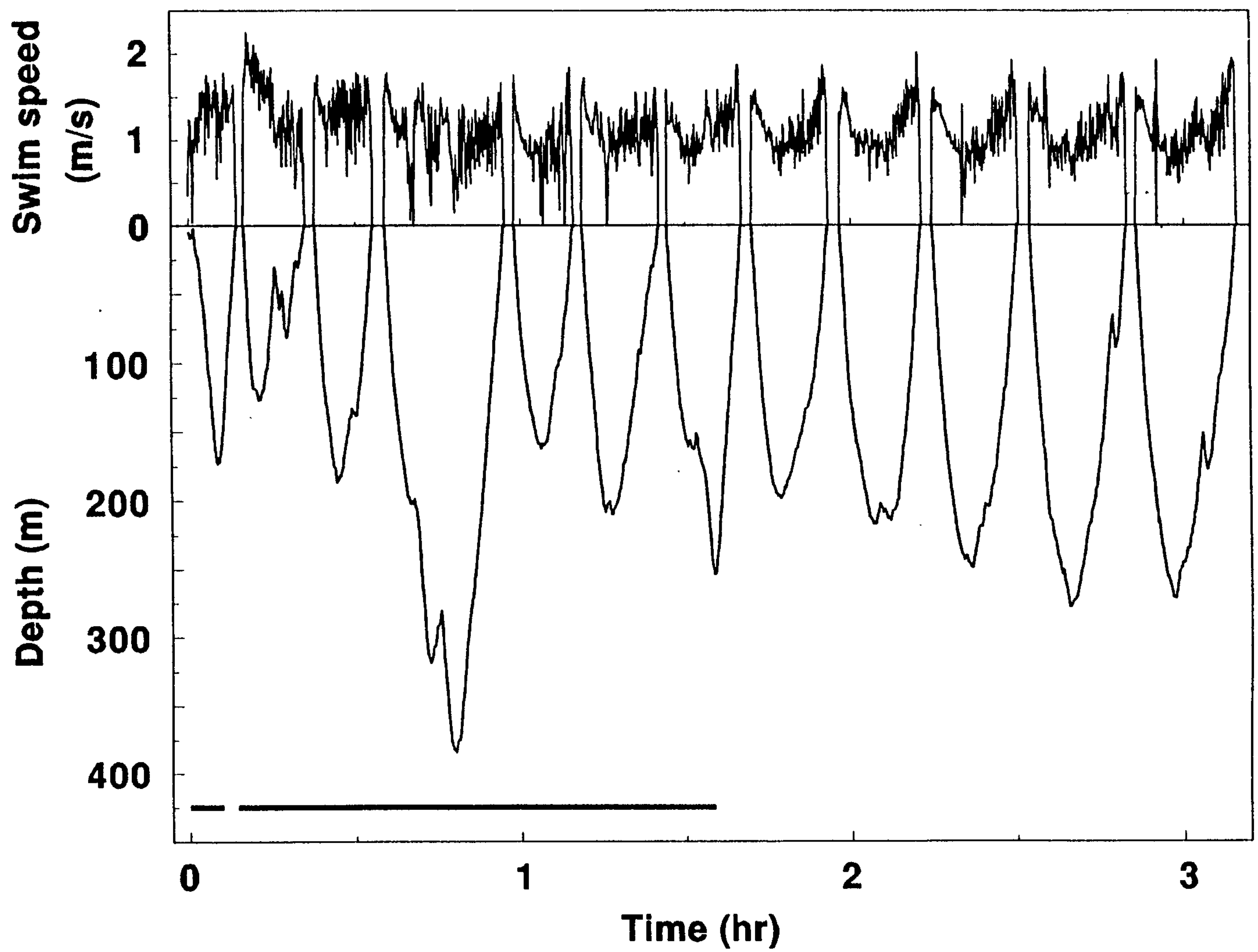
Swim speed (m/s)
Depth (m)
Time (min)



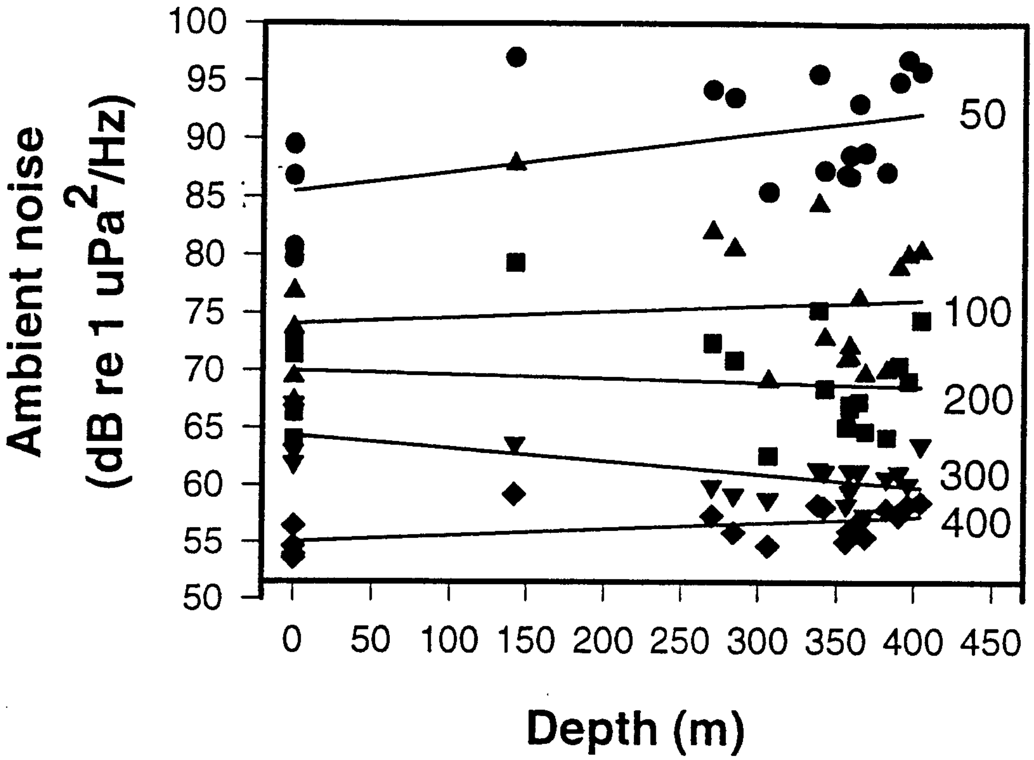
Frequency (kHz)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
2.0
4.0
6.0
8.0
10.0
Time (seconds)

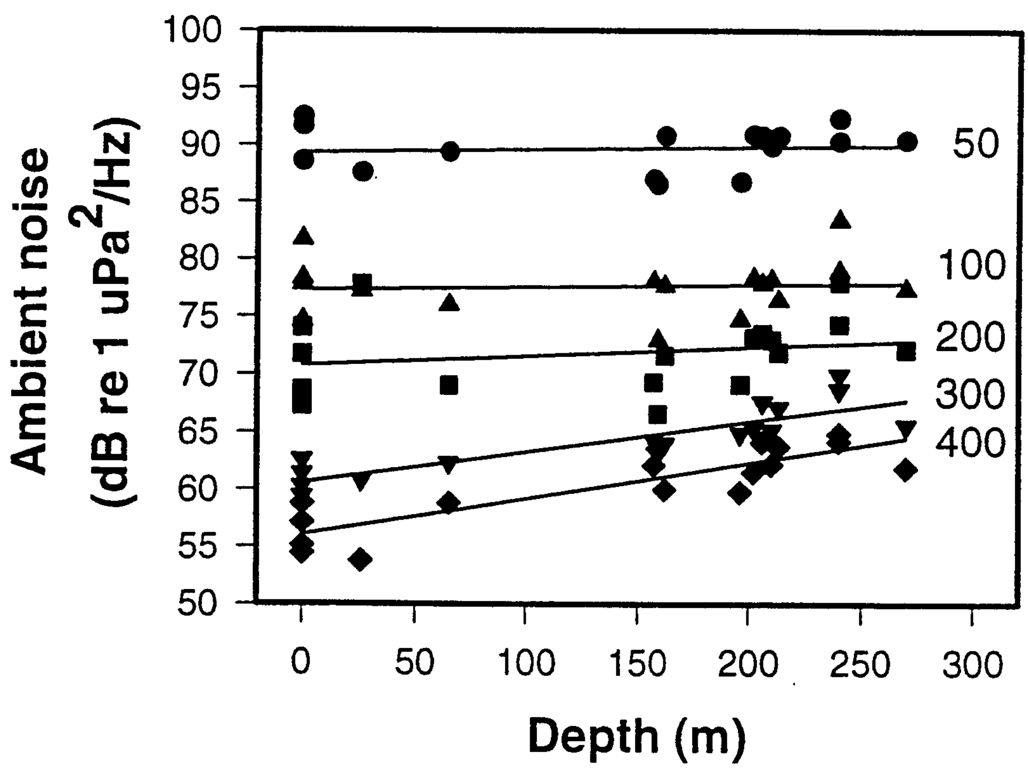

Depth (m)
0
100
200
300
400
500
0
1
2
3
Time (hr)

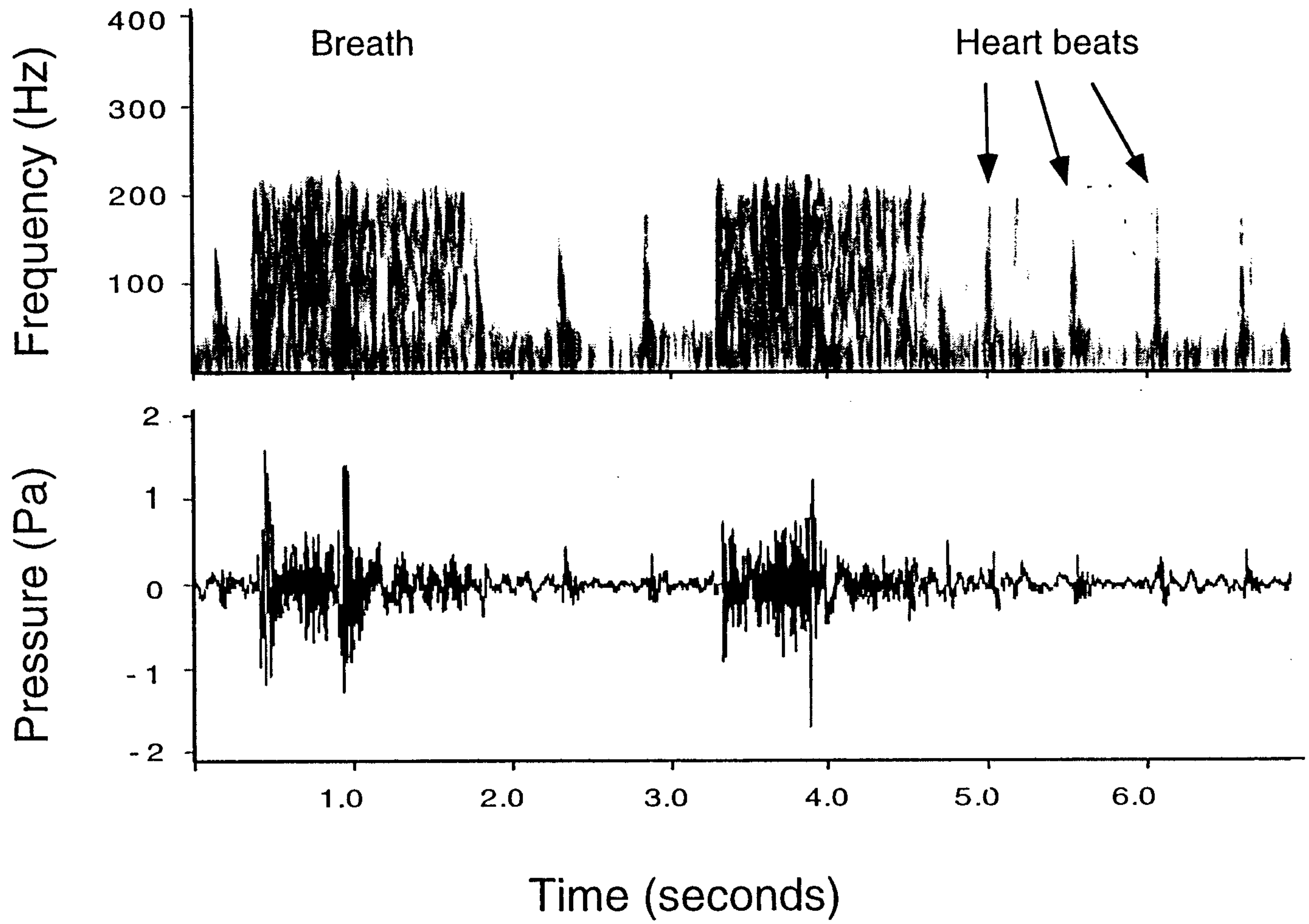

Frequency (kHz)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1.0
2.0
3.0
4.0
5.0
Time (seconds)

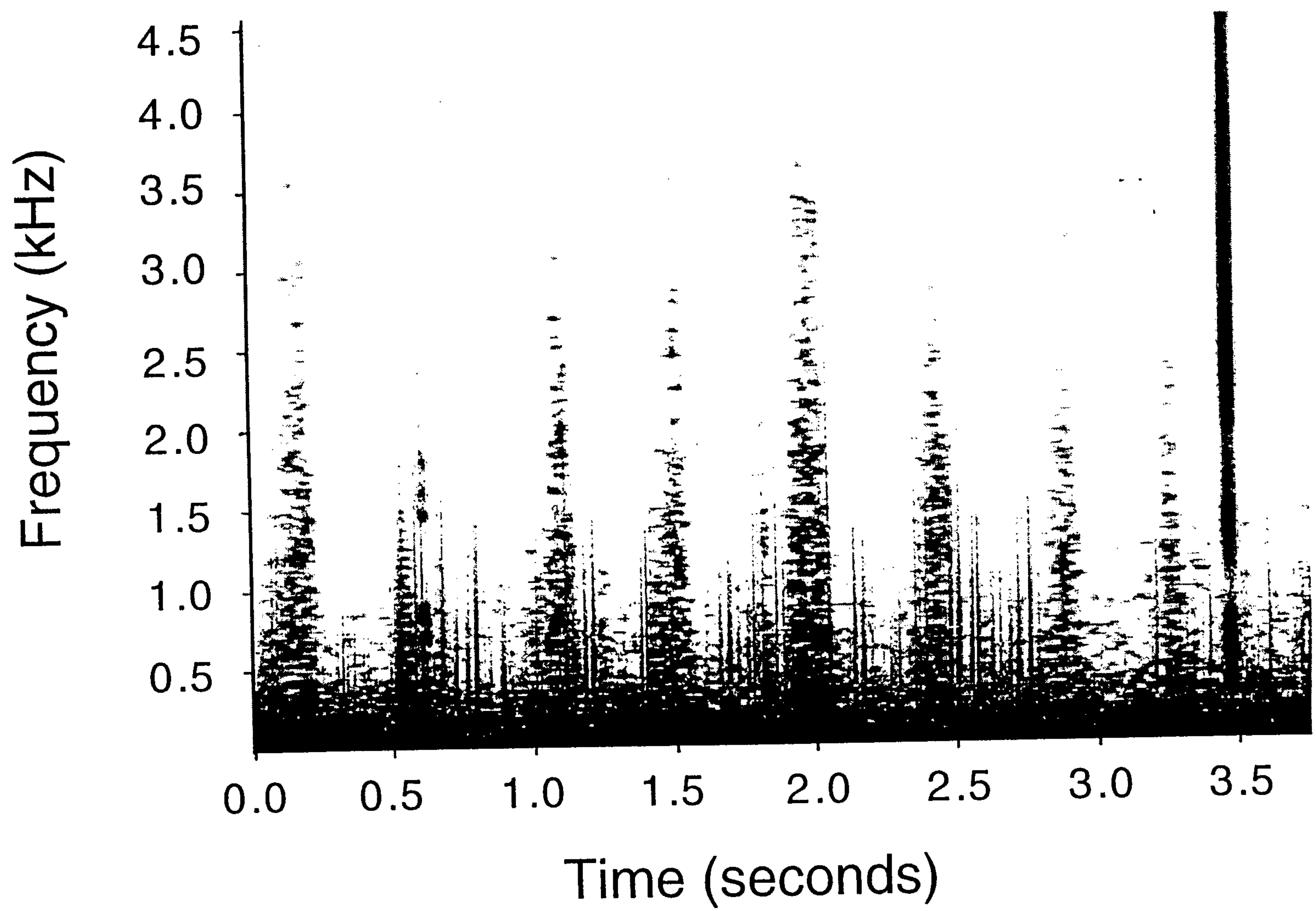


Swim speed (m/s)
2
1
0
100
200
300
400
Depth (m)
0
1
2
3
Time (hr)


Ambient noise
(dB re 1 uPa2/Hz)
100
95
90
85
80
75
70
65
60
55
50
0
50
100
150
200
250
300
350
400
450
Depth (m)
50
100
200
300
400


Ambient noise
(dB re 1 uPa2/Hz)
100
95
90
85
80
75
70
65
60
55
50
0
50
100
150
200
250
300
Depth (m)
50
100
200
300
400


Breath
Heart beats
Frequency (Hz)
400
300
200
100
Pressure (Pa)
2
1
0
- 1
- 2
1.0
2.0
3.0
4.0
5.0
6.0
Time (seconds)



Frequency (kHz)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Time (seconds)

Table 1. Vital statistics, release date and location, and instrument package components of six juvenile elephant seals translocated from Año Nuevo to Monterey Bay. All seals carried DAT recorders and radiotransmitters. Seals released in fall, 1994, were 1.8 years old; those released in spring, 1995, were 1.4 years old.

Name	Sex	Mass (kg)	Release Date & Time	Coordinates (°N, °W)	Water Depth (m)	Return Latency (days)	Time-Depth-Recorder	Satellite Tag	Record Switch	Syntactic Foam	Hydrophone	
											Orientation	Connection
94A	F	147.8	5/6/94 915	36.39 122.06	1200	3	Mk3	no	salt water	yes	forward	clamped
94B	F	190	9/21/94 740	36.39 122.06	1200	6	no	no	magnetic	yes	forward	clamped
94C	M	211.2	10/8/94 930	36.39 122.06	1200	*	Mk3	on head	magnetic	yes	forward	clamped
95A	F	160	4/11/95 1100	36.47 122.01	238	1	Mk3	on patch	magnetic	no	forward	potted
95B	F	181.7	4/17/95 1037	36.47 122.01	238	2	Mk3	on patch	magnetic	no	backward	potted
95C	F	173.5	4/28/95 1116	36.47 122.01	238	4	B-H	on patch	magnetic	no	backward	potted

*Did not return

Table 2. Summary diving statistics, and respiratory rate and heart rate data at the surface between dives, of translocated juvenile elephant seals returning to the Año Nuevo rookery. The ± figures are standard deviations. na = not available

Seal Number	Number of Dives	Mean Dive Depth (m)	Mean Dive Duration (min)	Mean Surface Interval (min)	Time on Surface (%)	Mean Breaths per Surface Interval	Mean Breathing Rate (breaths/min)	Mean Heart Rate (bpm)	Correlation Coefficient: Breathing Rate & Heart Rate
95A	13	na	12.6 ± 3.7	1.8 ± 0.2	13.5	42.2 ± 2.9	24.6 ± 1.6	118.8 ± 1.4	0.72
95B	10	370 ± 46	17.4 ± 2.2	2.4 ± 0.1	12.4	54.2 ± 1.1	22.6 ± 0.4	121.6 ± 0.9	0.39
95C	12	226 ± 68	14.1 ± 3.8	1.9 ± 0.1	12.4	41.4 ± 2.1	22.0 ± 1.0	117.0 ± 1.0	0.58